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TO WHICH IS ADDED A

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Translated from the German of Karl Braun,

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AND

A Bibliography of Works on Explosives.

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PREFACE.

THE subject of explosives is, chiefly through the labors of M. Berthelot, now recognized as a part of the extensive subject of thermo-chemistry. A certain amount of chemical action involved in any particular combustion, means to the chemist a determinate fixed amount of sensible heat evolved, and an equally determinate amount of possible mechanical effect. Thus the relative value of various explosive compounds may be determined with a fair degree of certainty from a knowledge of the chemical elements concerned.

The modern theory here recognized is the basis of the manufacture of the various forms of explosives which are now adapted to such a wide variety of purposes; the arts of peace requiring even more than the art of war.

In the Appendix will be found a valuable bibliography, prepared by Mr. W. H. Farrington, relating to the *constitution* and *preparation* of explosive substances. This is only a part of a more extensive list, which included *applications*, prepared by Mr. Farrington for *Van Nostrand's Monthly Record of Scientific Literature.* G. W. P.

Explosive Materials.

— BY —

M. P. E. BERTHELOT.

In presenting this translation to the public, I desire to express my thorough appreciation of the aid which I have received from Dr. T. O'Conor Sloane, E. M., of New York, and Prof. Chas. E. Munroe, Ph. D., of the United States Naval Academy, at Annapolis, Md. The former gentleman compared my manuscript with the original text before publication, while the latter revised my proofs after the article had been put in type. It gives me great pleasure to acknowledge my indebtedness to them.

M. B.

EXPLOSIVE MATERIALS.

I.

General Observations in the Force of Explosives.

1. The force of an explosive may be understood in two ways according to the different senses in which the word is applied, that is, it may be considered either as the pressure developed or as the work accomplished. It frequently happens that the word force is used to represent the *pressure* resulting from the explosive, or (to put it more definitely) that produced by the gas arising from the decomposition. It is this which is the cause of the bursting of shells and the breaking down of walls in mines.

But this definition is not complete, for the reason that hydraulic pressure would effect similar results without producing any notable ultimate effects, whereas certain mechanical results follow as the result of explosions, such as the noise, or the extended fracture of rocks, the projection of balls, of bullets, and of fragments from shells shattered by the explosion.

2. The following detailed list includes the principal applications of explosives in industrial and military arts.

First.—The bursting of shells by black powder or its substitutes.

Second.—The breaking of masses of cast or wrought iron, such as bears, which accumulate below the tap hole of cupolas, or which form in the crucibles of blast furnaces, causing the suspension of all work. Black powder is almost entirely without action on such material, and it becomes necessary to use some stronger agents, such as nitro-glycerin, or dynamite, or even compressed gun-cotton, in order to break into pieces the cast or wrought iron.

Third.—The destruction of metallic bridges by twisting, tearing, or otherwise removing them from their location, to prevent their use in times of war, with the utter ruin of their fragments either on land or under the water, so that the bridge cannot be reconstructed.

Fourth.—The breaking, rupturing and piercing of rails and metallic plates, such as armor or sheathing and the like.

Fifth.—The destroying or rendering useless of pieces of ordnance, steel, cast iron or bronze, either by bursting them with dynamite or blowing off the trunnions.

Sixth.—The blasting of rocks by means of dynamite, gun-cotton, or any of the various forms of black powder (gun powder, mine powder, etc.).

This blasting may have for its object the simple dislocation of the rocks, or else their reduction into smaller pieces, which remain *in situ* or are trimmed and piled in heaps for some industrial use, or they may be employed for some military operation. Finally, it is possible to pulverize the rocks into powder or into very small pieces · when it is desired to dig a hole or make an opening in the ground. The differences in rocks on account of their hardness, their tenacity, or their aquiferous or fissure-like character demand a great diversity in the use of explosives, which are necessary to produce any desired result.

Some very interesting applications of both dynamite and gun-cotton have resulted from submarine blasting and by their employment, it becomes possible to make constructions, which heretofore have been deemed impracticable.

Seventh.—The destruction and excavation of clay banks or earth works by dynamite and the digging of chambers and passages in clay or earth.

Eighth.—The demolition of all kinds of masonry, the destruction of bridges, tunnels, constructions of all sorts, galleries in mines, etc.

Ninth.—The breaking of ice and the removal of icicles by extensive displacement of the material; for this variety of work dynamite is especially adapted.

Tenth.—The breaking of wood by splitting, cutting, or tearing, such as the removal of standing timber by using dynamite in land clearing or in war ; the breaking down or overthrowing of palisades; the demolition and breaking up of piles under water; the tearing up and breaking of buried stumps of trees.

Eleventh.—The destruction of floating vessels; the breaking up of stranded ships or submarine wrecks.

Twelfth.—The destruction of torpedoes; of submarine or subterranean mines from a distance.

Thirteenth.—The projection of balls, bullets, shells, etc., from various weapons, guns, cannon, etc.

Fourteenth.—The projection of rockets by the combustion of an internal charge of powder.

Fifteenth.—The ignition by primers or detonators, which determine explosions in the main body of gunpowder or dynamite.

We shall not at present refer to the pyrotechnics, that is to say, the use of powder as the agent for producing lights and fireworks. The theory of these displays is entirely different from those which we are about to consider.

3. The different applications of explosives which we have just enumerated are due equally to the pressure and the work produced by these substances.

The *pressure* depends principally upon the nature of the gases formed, on their volume and on their temperature.

The *work* on the other hand is principally dependant upon the amount of heat given off, which is the criterion of the energy developed. In other words, the *maximum work* which an explosive substance is capable of producing is proportional to the quantity of heat given off in consequence of the chemical decomposition of the explosive, the substance being taken at the existing pressure and temperature, and its theoretical products reduced to the same conditions.

4. Let Q be this quantity of heat, expressed in calories, the corresponding effect translated into kilogrammeters would be according to the mechanical equivalent of heat, 425 Q. This figure

expresses the *potential energy* of the explosive. Without a doubt, this is a limit that is never reached in practice, but it is necessary to be familiar with it as the only absolute term for comparison.

5. The effective transformation of this energy into work depends upon the volume of gas, the temperature, and the law of expansion. This transformation is never complete; and, moreover, only a portion of the work developed is utilized in the application. For instance, in guns, the work which communicates to the projectile its mechanical energy is all that is taken into account; it represents the actual amount utilized, while the work used up in heating the walls of the weapon, and in moving the gases and the air projected, is lost. An important fraction of the energy always remains unused in the form of heat locked up in the gases, or else communicated to the projectile, to the gun, etc.

The calculation of this diverse distribution of energy between the heating, the mechanical work done, the mechanical energy communicated, and vibratory movements of the ground and of the air, is most complicated.

6. The following are some general ideas in this connection, ideas which we think it best to present at this juncture. In considering the work for which explosives are to be employed, they are distinguished as *strong powders* and *weak powders*, *rapid powders*, and *slow powders*.

7. *Strong and rapid powders.*—The materials whose chemical decomposition takes place very rapidly, such as mercury fulminate, produce principally the effect of crushing rocks *in situ*, or breaking the shells of hollow projectiles into a multitude of small fragments, the elasticity of the entire mass not having time to come into play; they constitute what are called the *breaking powders*.

Furthermore, the mechanical energy of translation communicated to particles contiguous to the powder, becomes predominant in consequence of the sudden production of the enormous pressures which is particularly characteristic of this class of powders. It influences in a special manner the surrounding gases, the molecules of which find themselves set in motion all of a sudden with a rapidity very much greater than that of their actual change of place, which is, as is known, closely comparable to the exact velocity of sound in gases; in consequence, the molecules of gas tend to accumulate, the one on top of the other, and to produce the effects of a shock, and even of rupture, which may be compared to those which result from the shock or the pressure of an extremely hard, solid body.

Such are the extreme effects produced by the almost instantaneous explosion of a breaking powder. But if the decomposition is retarded a little, and if the potential energy is considerable (*strong powders*), the explosive has a tendency to produce a tearing or shearing in the lines of the least resistance, even of metals having the greatest resisting powers. These effects extend for some distance into the mass of compact substances of moderate tenacity, and the result is dislocation. They produce these results without projection, provided that the masses to which the movement is communicated are of sufficient size.

In the employment of strong and breaking powders, it is not necessary to tamp at all, or but little, since the communication of the pressure takes place by mere contact before the products formed have time to drive away the compressed air.

It is thus, that a feeble charge of dynamite placed in the open air on a hewn stone, and covered by a simple sand-bag, is sufficient to break that stone into small pieces. A single cartridge containing 150 grams of dynamite (of 75 per cent.), will, in this way, break a block having a surface equal to 60 – 80 square decimeters and a thickness of 40 centimeters. The piece will be broken up following the cracks which radiate from the center of the explosion, and is analogous to that which would be produced by the impact of a mass of iron falling from a great height

In a word, the effect is that of a gigantic shock, and is extremely brusque. Besides this, dynamite may be used to break a block according to a given design, as if by a wedge. All that is necessary is that a furrow shall be marked along the surface, with a central drill-hole in which the charge is placed.

It is in consequence of this means of propagating the pressure, that the depth of a blast-hole may be made much less when dynamite is used. This is not all. In a blast-hole, the effect of the layers and crevices in the rock do not seriously influence the action of such a powder, providing, however, that the layers or crevices are not directed towards the center of the shock. These powders are also greatly preferred for displacing fissured and aquiferous territory; they excel all others in tearing down a sand bank, or for enlarging a stony excavation. The conditions under which they act, are such that they may be employed equally well for driving a shaft in the ground, of medium size, perpendicular to the surface, always in the direction of the least resistance, and without paying any attention to the breaking of rocks that may lay in their pathway.

With such powders, the effect of successive explosions in the same chamber are cumulative, that is to say, the fissures produced by the first shock are increased with the second; by taking advantage of this circumstance, it is possible to obtain pieces of much greater dimensions than could have been obtained by one single operation, using the entire quantity of dynamite.

These different properties which characterize the action of dynamite, lead us to regard it as the type of the strong and rapid powders.

8. *Strong and Slow Powders.*—Black powder or gunpowder is also a strong powder, although for equal weight, it is of considerable less power than dynamite; but at the same time it is a slow powder. In consequence it produces a pressure which increases more slowly, and is of longer duration. It does not break the

material *in situ* into small fragments. This quality, which is very important for certain purposes, for instance, in the mining of coal, where it is desirable to break the material into as large pieces as possible, since this substance is quite brittle and easily cracked. Black powder will also break an empty projectile into a smaller number of pieces with less effort, and these can then be driven further for the same expenditure of energy, less of it having been consumed in the work of rending.

On the other hand, black powder has less effect, and does not break rock in a mine in a desired direction when the mass is very compact and strongly adherent. It is easily turned aside, especially if the tamping or charge has not a greater resistance than that of the direction in which the rock has the least resistance, and the masses which become detached in the direction of the least resistance are frequently thrown to some little distance by black powder. On this account it is necessary to make the drill holes very deep and sometimes inclined at an angle of 45° for the purpose of giving a convenient length to the tamping, which is an element of expense.

The cracks and cleavages adjoining the charge lessen the effect of the explosion. They weaken it until the effect is nullified; if these cross the drill holes the expansion of the gases from the powder frequently takes place in the interior cavities, it is then that the mine *blows.* Also, in fissured rocks much time is often lost in closing up with rammed clay the cracks which are connected with the drill hole, whereas this work is unnecessary when dynamite is used. For similar reasons it is of little value in blasting argillaceous or aquiferous rocks, in calcareous tufas, in conglomerates, and in beds of sand of high resistance, in one direction, and slight resistance in others. It has little effect, for directly opposite reasons, in very hard and tenacious rocks, such as quartzite and certain felspars.

These circumstances, in addition to the fact that black powder has less force (the effect of one part of dynamite is regarded in practice as equivalent to two and one-half parts of black powder), explain the preference given to dynamite in most mining operations.

Nevertheless, black powder possesses certain advantages due to the gradual increase of the pressure which allows it to transmit its effects to a distance, for instance, in beds of coal, or better still, in wood, following the direction of the fibers. In recent earthworks, the pressures, if too suddenly produced by the quick powders, will shatter the mass and expend themselves in local work without much effect, while the slower tension of black powder displaces the earth and throws it in the direction of the least resistance.

From these details and these examples, we see what part the rapidity of the explosion plays in the transformation of energy into work.

9. Finally, the force of the explosion

may be expressed in terms of the pressures produced, and by the work which they perform. The pressure results from the volume which the gases occupy at the temperature of the explosion. The work is due to the heat produced, and to the rapidity with which the gases are developed. These fundamental conditions —volume of the gases and the heat—are the consequences of the chemical decomposition; any reactions which liberate gases, or which augment the volume of a previously existing gas, may be the cause of an explosion. Therefore, in consideration of the foregoing observation, to define the force of an explosive, the following data are necessary:

First. *The chemical composition of the explosive.*

Second. *The composition of the products of explosion.*

The latter may vary during the different periods of temperature which succeed each other from the first moment of ignition; it is also necessary to take the *dissociation* into account.

These three elements, the chemical composition of the exploding substance, the chemical composition of the products of the explosion, and finally the dissociation will be studied under the general title of *chemical composition.*

Also, it is desirable to define the following:

1. The *quantity of heat* given off during the reaction.

2. The volume of the gases formed under normal pressure.

These propositions are also obtainable from a knowledge of the two first in all reactions which are positively known.

3. The rapidity with which the reaction takes place gives rise to the following studies, which are essential in order to be able to furnish a complete definition of explosives.

Origin of the reaction—The rapidity of the increase of the reactions.

To this sequence of ideas there should be attached a collection of phenomena, which are designated by the name of *explosions by influence.*

These phenomena, which have only been known for a few years, have seemed to us of sufficient importance to be separately considered with their accompanying developments.

In the treatment of these questions, we shall endeavor to cover all of the general ideas known at present concerning explosive substances.

II.

The Duration of the Explosive Reactions.

§ 1.—*Origin of the Reactions.*

We shall now take up the consideration of the chemical transformation of explosives, from the point of view of their origin and rapidity.

1. We will at first treat of its origin, that is to say, of the conditions which determine the commencement of the reaction. This, once started, maintains itself, and increases either by a simple progressive burning or by an almost instantaneous detonation.

Thus far, artillerists have expressed this origin by the expression "*set on fire*," which implies that fire is applied locally to begin with; but the study of explosives shows us that the origin of the reaction may arise equally as well from a shock, from pressure, from friction, or from some other analogous mechanical force.

At first, suppose that it is necessary to refer all explosive reactions to an original heating, which is increased step by step, by successively bringing all the particles of the substance up to the temperature of its decomposition. The shock, the pressure, the mechanical conditions are not efficacious except as they determine this first heating, according to mechanisms otherwise different, and to which we shall return in the following paragraphs.

2. This being understood, the decomposition of the same material can take place at widely varying temperatures, but with equal rapidity, a material slowly decomposed at a

given temperature being able to exist at much higher temperatures, though for a time which decreases as the temperature rises. Elsewhere I have explained all of this theory, (*Essai de Mecanique Chimique*, Vol. II., p. 58, *et seq.*), and it is recalled only for the purpose of thoroughly fixing the ideas which are developed there. It plays a very important rôle in the explanation of the mode of formation of the secondary compounds produced in the explosion of powder; several of these compounds, such as formene, ammonia, and nitric acid are formed simultaneously, at a temperature which destroys them slowly, if it be maintained during a sufficient length of time; but the abruptness of cooling preserves the compounds from the destruction toward which they would hasten, because it brings them to temperatures at which they are perfectly stable.

3. It is desirable here to introduce some statements regarding the *sensibility of explosives.* This sensibility is equally dependent on the conditions of heating

and on the method of propagation of the reactions. It varies according to these conditions. Some substances are sensitive to the slightest elevation of temperatures, others to a shock, properly so-called, others detonate at the least friction. Silver oxalate detonates about 130°, nitrogen sulphide about 207°, mercury fulminate at about the same figure, somewhere near 190°, nevertheless, the fulminate is much more sensitive to a shock and friction than the nitrogen sulphide and the silver oxalate. Thus we discern the existence of the special properties depending upon the individual structure of each substance, particularly of the solids. But there also exist general conditions which it will be useful to define here.

4. The sensibility is greatest for the same substance when operated on at the highest initial temperature, that is to say, at the temperature nearest to that at which the substance begins to spontaneously decompose.

A fortiori the sensitiveness will be still further increased, if this limit is exceeded, that is to say if conditions occur where a slow decomposition may be transformed by the least heating into a rapid decomposition. A substance within these limits may be said to be in a state of *chemical tension*, an expression which is sometimes erroneously employed with reference to stable bodies, or for mixtures which have no habitual tendency to enter into a spontaneous reaction.

We have an example of such a case in *celluloid*, a body which does not detonate at ordinary temperatures, when struck by a hammer, but acquires the property of detonating when it is heated up to the point where it becomes soft, that is to say, up to about 160° to 180°, a locality which is near the temperature at which the substance decomposes.

5. When two different explosives which are decomposed at the same temperature, and with similar rapidity are compared, their relative sensitiveness to shock and to friction at a lower tempera-

ture depends primarily on the mass of the substance on which the work of the shock expends itself; that is to say, it depends upon the cohesion of the substance which governs the transformation of the shock into heat. Cohesion, likewise, interferes with direct ignition, as the same quantity of heat as that produced by the combination of the first portions could elevate to the temperature of decomposition, a small quantity of matter to which it is exclusively applied, while, as it is distributed over a larger mass, the temperature of that mass will not be brought up to the required degree.

6. The mass heated remaining the same, and the materials being different, the sensitiveness will depend upon the temperature of decomposition, which, for example, is lower for potassium chlorate than for the nitrate; the chlorate gunpowder is therefore more sensitive than that made with the nitrate.

7. The sensitiveness depends, furthermore, on the quantity of heat set free by the decomposition, that is to say, the

sensitiveness will be greater, other things being equal, if the reaction gives off a greater amount of heat.

8. This same quantity of heat will produce different effects in acting on the same weight of substance according to its specific heat. For instance if potassium chlorate, whose specific heat is 0.209, be substituted for an equal weight of potassium nitrate, whose specific heat is 0.239, in the composition of an explosive mixture, a powder more sensitive than the nitrate powder would be produced. This condition acts in concert with the lower temperature of decomposition and with the absence of cohesion in chlorate powders, so as to render them particularly dangerous.

§ 2.—*Molecular Rapidity of the Reaction.*

1. The chemical transformation in a detonating mass is propagated with a certain rapidity, a knowledge of which is desirable for theory as well as in practice. In reality the velocity with which

the gases are given off depends on it, and in consequence the rapidity communicated to projectiles in guns, as well as the effects produced in mines in throwing down rocks or in removing obstacles for engineering purposes. For, the heat given off by a given reaction may be employed almost entirely to heat the gases and to increase the pressure, provided the reaction is very rapid, while if the reaction is made slower it is dissipated without effect by radiation or by conductivity.

A given quantity of an explosive may in this manner crush, *in situ*, such portions of rock as it comes in contact with, its energy being consumed without any result, from an industrial point of view, on account of its instantaneous decomposition. If the development of the gases is less rapid, but is still quite fast, an equal quantity of explosive may, on the other hand, dislocate the rock by de veloping extended fissures and sharply striking those portions of rock which are the nearest, a result which is sought for by miners. It may also produce elastic displacements and an undulatory movement of the soil without any local disturbance, if the pressures are developed sufficiently slow, so that the rocks shall have time to be displaced *en masse*, in which case the explosive will be found to have produced scarcely any useful result.

This question of the quickness of reactions plays an important part in the studies relating to explosives, and therefore I am led at this point to collate the experiences and results which they have produced.

2. The quickness of a reaction may be considered in two ways, (1) if it is to act upon a homogeneous system, and especially a gaseous system, surrounded by conditions of pressure and temperature identical in all its parts; (2) if the system is subjected at one point to an elevation of temperature or to a shock capable of determining an explosion, which is then propagated step by step.

It is desirable to begin with the examination of the first case, which serves as a basis for the entire theory.

3. Having, therefore, a certain body, or a certain mixture, capable of undergoing a chemical transformation when the entire mass is placed under the same conditions of temperature, of pressure, or of vibratory motion, etc., it appears as if the reactions should be instantaneously developed in all parts at once. The sudden explosions of nitrogen chloride and nitro-glycerin seem at first sight favorable to this conception. Nevertheless, a closer observation proves that the molecular reactions as a general thing consume a certain amount of time for their accomplishment, even when they are giving off heat.

Such, for example, is the decomposition of formic acid into hydrogen and carbon dioxide, which furnishes experiments that are easy to follow on account of the slowness with which this decomposition takes place. Operating in a closed vessel, kept at a fixed temperature of 260°, it requires quite a length of time. And yet this reaction gives 5.8 calories to each equivalent of formic acid, that is to say, 126 calories to the gram.*

4. The following are other examples of reactions which give off a great quantity of heat without being instantaneous. Thus acetylene, changed into benzine at a dark red heat by a slow reaction, gives off, without increase of volume, one and a-half times as much heat as a detonating mixture composed of oxygen and hydrogen in the proportions which form water, that is, 85.5 calories for 33.6 liters of acetylene (reduced at 0° and to 0. 760 m.m.) in place of 59 calories produced by the formation of steam, by means of the same volume of detonating gas. It is about four times the amount of heat given off by the same weight of chlorate powder, that is 2,192 calories for each gram of acetylene transformed, instead of 590.6 calories for each gram of potassium chlorate powder.

* *Essai de Mécanique Chimique*, Vol. II., p. 17.

Cyanogen gives off three times as much heat (1,435 calories to the gram) as the same weight of chlorate powder; or again, twice the amount of heat disengaged by its own volume, 33.6 liters, of a detonating mixture formed of oxyhydric gas; 112 calories instead of 59, when the so-called cyanogen is decomposed into carbon and nitrogen by the electric spark. Although the carbon begins to be precipitated almost immediately, still the cyanogen does not detonate in consequence of the spark, a fact which demonstrates the slowness of the reaction thus determined. Under other conditions, however, the cyanogen and the acetylene may be decomposed into their elements accompanied by detonation, but it is not by simply heating nor by the action of the electric spark.

I might go on multiplying such facts† which refer to the explosive bodies properly so-called when they are kept at a temperature slightly lower than that which determines the explosion. Silver

† *Annales de Chimie et Physique*, 4th series, 18, 142.

oxalate, for instance, slowly decomposes at 100°, whereas, at a temperature a little above this it detonates strongly.

5. In brief, all molecular reactions, operated by simple heating at a constant temperature, in the midst of a homogeneous body, and surrounded by conditions which appear identical for all its parts, are effected by a characteristic coefficient depending on the duration of the reaction. This coefficient varies with the temperature, the pressure and the relative proportions; it plays an important rôle in the study of the powers of destruction among explosive compounds.

6. Let us follow out this explanation. The greater or less duration of a reaction does not change the quantity of heat given off by the total transformation of a given weight of explosive material. But if the gases which are formed expand in volume in consequence of the change of capacity caused by the escape of the projectile, or else by the cooling due to the contact with the walls; under such circumstances the in-

itial pressures will be proportionally less than when the transformation of a given weight of an explosive is of longer duration.

On the other hand, when a very rapid transformation of the entire mass in the midst of a closed vessel, added to the absence of the phenomena of dissociation, permits the initial pressures to reach the extent of their theoretical limits, or to approach them, it will be extremely difficult to make vessels strong enough to retain the gases of explosion.

7. The same state of affairs prevails, not only for an explosive body placed in a fixed and resisting volume, but also for the same body placed in a thin envelope, or beneath a layer of water, or even in the open air. In reality when the duration of the reactions decreases beyond measure, the gases given off develop pressures which increase with immense rapidity, so rapidly, indeed, that the enveloping bodies—solids, liquids, or gases—have not sufficient time to move and yield gradually to the pressure; these

bodies oppose the pressure of the gas with a resistance comparable to that of a fixed wall. It is known that a pellicle of water on the surface of nitrogen chloride is sufficient to produce such results. The more nearly instantaneous the reaction is the more nearly the initial pressure, even in an open vessel, approaches the theoretical pressure, the latter being calculated for a case of decomposition under a constant volume, entirely filled by the explosive substance. It is in this way that we can explain the extraordinary effects of destruction produced by mercury fulminate, nitro-glycerin, or compressed gun-cotton.

8. *As a general thing, any reaction that gives off heat is capable of producing explosive phenomena, provided, however, that it produces gaseous products*, and this for several reasons—First: *The rapidity of the reactions in a homogeneous system*, other things being equal, *increases with the temperature.** It even increases according to a very rapid law,

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* *Essai de Méchanique Chimique*, Vol. II., p. 64.

as has already been shown by my experiments on the ethers; * hence the rapidity may be represented by an exponential function of the temperature, a function whose numerical value in the formation of acetic acid is 22,000 greater at 200° than when it is in the neighborhood of 7°. Secondly: *The temperature of the system increases, at least up to a certain limit, in the same degree as the reaction.*

Let there be a system capable of giving off heat in consequence of its chemical transformation; if this system is confined in a position where it can neither give up nor receive the least quantity of heat, the temperature of the system will continue to rise without stopping until it reaches a limit represented by a number which is obtained by dividing the amount of heat given off, by the specific heat of the system. In addition, the rapidity with which this system tends towards this limit will increase in proportion as the

* *Essai de Mécanique Chimique*, Vol. II., p. 93.

elevation of the temperature already produced by the reaction, is greater.

In a gaseous system confined in a fixed space, the acceleration will become greater still, at least in the beginning, and that in consequence of the effect produced by the pressure, which pressure increases necessarily on account of the elevation of the temperature. For I have established the fact, that, all else being equal, in operating at a fixed temperature the reactions take place more rapidly in liquid mixtures that in gaseous mixtures; it is especially noticeable that in gaseous mixtures the reactions are the more rapid as the pressure is the greater. * In a word:

Third. The speed of the reaction in a homogeneous system increases as the condensation of the substance progresses, or more simply *with the pressure in the gaseous systems.*†

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* *Essai de Méchanique Chimique*, Vol. II., p. 94.

† In liquid or solid systems, the pressure on the other hand, exercises but little influence, that is according to my investigations. A circumstance which is explicable because it is produced in consequence of the state of condensation of the material.

Thus, in a closed vessel supposed to be impermeable to heat, the initial speed of the reaction continues to increase, for the double reason that the temperature is continually being elevated and that the pressure of the gas increases without stopping. Nevertheless, the influence of the pressure should be more apparent at the beginning than at the end of the experiment; provided, however, that the part which is not in combination, continually diminishes until the moment arrives when the proper tension of this part, considered by itself, ceases to increase in consequence of the heating; from that time on, it tends to diminish until it becomes *nil.*

9. *The speed of the reactions in a homogeneous system depends upon the relative proportions of the components.*— In operating at a *constant temperature* the combination is generally accelerated by the presence of one or the other of the components.

On the other hand, at a constant temperature, the reaction is retarded by the pressure of an inert substance which has the effect of diminishing the state of condensation existing in the substance.

At a variable temperature the reactions are retarded *a fortiori* by the presence of an inert body, such as for instance, the nitrogen of the air, or the silica of ordinary dynamite, since this body by absorbing the heat lowers the temperature of the system without exerting any special influence to hasten the reaction by its presence.

The reaction is generally slower at a variable temperature in the presence of an excess of one of the components, for if the operation is effected with equal equivalents, the necessity of heating this excess is more than counterbalanced by its accelerating influence.

It is clear that if the proportion of inert substance is such that the temperature of the system cannot be elevated to a degree necessary for the combination to continue of itself, the reaction will cease to be explosive and perhaps will not be propagated.

Thus it is that the character of an explosive body may be changed by simply mixing it with an inert body. We shall now cite some important facts. A seventy-five per cent. dynamite is not as brisante as pure nitro-glycerin, nevertheless, such a dynamite cannot be used for charging shells, for they might explode before leaving the cannon through the influence of the initial shock of the powder. Fifty or sixty per cent. dynamite, on the other hand, may be used with hollow projectiles and may be fired without giving rise to any injury to the ordnance.

This is not all, in using sixty per cent. dynamite, the projectile may be made to explode at the point it reaches without requiring any special priming, as for instance when its progress is stopped by a body of considerable resistance, such as a plate of iron, the elevation of temperature caused by this sudden arrest is sufficient to determine an explosion. But if the nitro-glycerin be reduced to thirty or forty per cent., a projectile charged with such a dynamite, requires a percussion fuse, in order to produce an explosion, similar to those used for black gunpowder. Such a dynamite presents scarcely any advantages over ordinary gunpowder.

It is an important observation that the velocity of inflammation of an explosive substance diminishes considerably as we approach those proportions of mixture with an inert body which correspond to the limits of inflammability. It follows then, that as these limits are approached the burning becomes uncertain and the explosive character of the phenomena ceases to be manifested.

10. These general relations having been established for a system such that all the heat which it gives off may be used to elevate its temperature. Let us examine the real condition of affairs, that in which the system gives a portion of its heat to the surrounding bodies by either radiation or conduction. The initial speed of the reactions, and the mass of the substances used, play an important part. In reality,

on all occasions, when the speed of the reactions is not great, a portion of the heat would, to a certain extent, be dissipated, and the rise of its temperature soon reach a fixed limit.

This limit will be one at which the loss of heat produced by the external action is equal to the gain due to the internal reactions of the system; in this case the reaction takes place with a certain rapidity, constant or almost so, without becoming explosive. Such is the case with deflagrating substances.

This is also the case (in a generally slow order) with explosive substances which decompose spontaneously. But if the mass with which the operation is conducted be increased, supposing it to be confined in a fixed space, the amount of heat lost by radiation or conduction at a given temperature will vary but little, and the entire amount of heat produced internally will be increased.

Thus, the temperature of the system would be higher either when it tends toward a new limit superior to the preceding, or when its growth becomes more and more rapid, and finally explosive in consequence of the correlative growth of the pressures. This same acceleration, depending on the pressures and the speed of the reactions, plays an important role in the interpretation of the effects produced by tamping. Besides, it is that all deflagrating are changed into detonating mixtures when the mass confined in a given space is increased.

The difference between the methods of decomposition of an explosive material, according as its mass is greater or less, deserves especial attention, for it recurs frequently in practical applications.

11. This is observed, even in the case where an exit is open to the gases of the explosion. If the explosive mass is of sufficient size, the decomposition of a deflagrating substance where gases are given off through a narrow opening, may be changed during explosion, when the opening is made narrower, in such a way that the pressure and the internal temperature may be increased towards a given

limit. The same remark may be applied to spontaneous decompositions, occurring in large masses of matter. Beginning slowly at ordinary temperatures, their rapidity increases under the influence of the rise in temperature which they determine; and it may happen that this will change the character of the decomposition, by causing a new reaction, giving off more heat, to follow the initial reaction. The elevation of the temperature of the mass increases and hastens until it produces a violent reaction and a general explosion.

12. These facts which are frequently observed in laboratories, have been quoted to explain the spontaneous explosions of gun cotton and nitro-glycerin. They lead to the belief that an explosive substance which has begun to decompose is particularly dangerous. Such general explosions are produced not only in explosives that are contained in very solid vessels, but also in those which are held in vessels that are slightly resisting, such as boxes of wood or thin metallic cases and even on substances heaped up in the open air, when the accumulation of the substance allows the temperature to be raised spontaneously and by the reaction induced to become more and more accelerated. They may take place equally as well in substances divided into very small quantities, provided that the particles are so near to each other that the mechanical effects may be accumulated and produce a common result. In their preservation and use the same precautions should be followed, just as if all the portions of the explosive were collected in a single mass. These are consequences which are theoretically possible and which are often demonstrated to be practically correct by the accidental occurence of terrible catastrophes.

13. In fact, the experiments made by the Birmingham Chamber of Commerce relative to the transportation and storage of caps, showed that the capsules, each containing 15 mgrs. of fulminate, would not explode in mass, nor by the influence of a shock, nor when crushed by the

wheel of a locomotive, nor when they were placed in the center of an incandescent muffle, or when in the midst of a burning hearth.

But if the weight of the fulminate contained in the capsule is considerably increased, the case becomes different. The sense of security which the first trials excited has ceased even in England, in consequence of an explosion on the Thames of a boat which was loaded with detonating caps. Experience has shown, beyond a doubt, that the explosion of a single powerful capsule of fulminate is sufficient to cause that of all the capsules placed in the same box; if the box itself explodes the neighboring boxes will detonate equally as well. It is in consequence of similar phenomena that the small fulminating caps which are sold as playthings to children, have so frequently been the cause of serious accidents.

At Vannes, near Paris, a child was amusing itself by exploding such a cap between the blades of a pair of scissors.

Two packages of 600 caps each, which were laying on the table close at hand went off at the same moment; the child was killed, the chair destroyed, and the floor injured.

We also cite the explosion that occurred in the Rue Beranger, at Paris, on May 14, 1878, which was produced by a mass of fulminating caps that were intended for children's toys. These caps had the following composition: one kind called single consisted of—

Potassium chlorate......	12	parts.
Amorphous phosphorus..	6	"
Lead oxide............	12	"
Resin	1	"

and those called double were made of a mixture of—

Potassium chlorate.....	9	parts.
Amorphous phosphorus	1	"
Antimony sulphide.....	1	"
Sulphur sublimed......	0.25	"
Nitre	0.25	"

The latter were more sensitive to friction, and on an average weighed 10 mgrs.

each. Six to eight million caps of this description done up in rows of five and pasted on strips of paper, were piled up in the store in boxes containing a gross in each. Some one of these individual caps was set off by an accident, whose origin was never known, and a general explosion ensued. Of a sudden the house was thrown down, its facade being destroyed by hurling the trimmed stones out of their positions. A stone, a meter cube in size, was thrown to a distance of 52 meters, and a large portion of the adjoining house was also ruined; fourteen persons were killed on the spot and sixteen wounded.

These terrible effects are explained when it is recollected that the explosive material contained in the caps weighed about 64 kilogrms., and according to the composition of the substance that its force was equal to 226 kilogrms. of black powder.*

* These facts are taken from the report made by the Inquest Commission.

It is, therefore, of the greatest importance that persons having explosives in their charge should be familiar with these truths and facts, and adopt such precautions as will prevent the explosion of the entire mass.

III.

§ 3.—*Speed of the Propagation of the Reaction.*

1. Let us now examine the case of a homogeneous system, but whose various parts are exposed to different conditions, such as those which arise from being ignited at one point or from a local shock. In order to propogate the transformation in a mass which detonates, and which is not submitted to the same action at all of its points, it is necessary that the same physical conditions of temperature, of pressure, etc., which prevail at one point of action, should successively be produced and propogated, molecule by molecule, through all portions of the mass.

In this connection the numerous works of artillerists on the rapidity of combustion of ordinary gun-powder, and of that of gun-cotton, are well known,* a capacity which varies according to the physical structure of the powders and their chemical composition. We shall presently examine these results as well as those observed in explosive mixtures of gases, that is to say the observations bearing on the rapidity of the combustion of mixtures of oxygen and hydrogen, or of carbon monoxide or gaseous hydrocarbons.

Then we shall give some new and unexpected results furnished from the study of gun-cotton and of nitro-glycerin, the new theory of the functions of caps, the distinction thus far ignored between the simple ignition and the true detonation of explosives, a distinction which my recent investigations extend to even gaseous mixtures themselves, and we shall seek to harmonize their differences with theoretical ideas.

* Piobert, Traite d' artillerie, partie theorique.

2. According to Piobert, the rapidity of the combustion of powder in the open air observed on prisms of known length, placed vertically, and whose lateral faces were greased in order to insure regularity in the phenomena, has been found to be included between 10 and 13 mm. to the second in gun-powder. Otherwise it varies in inverse proportion to the apparent density of the powder.

3. The rapidity of combustion of powder depends to a great extent on the pressure of the air or the surrounding gases.

Near the end of the seventeenth century Boyle made some experiments on the combustion of powder in vacuo, and observed that grains of powder thrown on a red-hot iron in this condition, melt without detonating. If the operation is conducted with a sufficient number of grains, towards the end an explosion will take place. There is no doubt that this is because the conditions of pressure are changed.

Huygens repeated the same experiments by igniting the powder with a burning-glass which concentrated the solar rays.

If the heating is progressive, (an effect which may be produced by a piece of glowing charcoal) then at pleasure the sulphur may be sublimed and the homogeneity of the mixture destroyed, or else according to Hawksbee (1702) the powder will be melted.

These experiments have been frequently repeated with different modifications, such as the employment of a red-hot platinum wire, heated by electricity, and then used to ignite the powder in vacuo.—(Abel). M. Bianchi has in this manner determined that gun-cotton is slowly decomposed in vacuo before its explosion, and a similar result with nitro-glycerin has been reached by Messrs. Heeren and Abel.

Mercury fulminate, on the other hand, detonates in vacuo when brought in contact with a piece of brass wire which has been heated red-hot, but the detonation does not extend to the grains which are not contiguous to it, as it does when under atmospheric pressure.

4. Not only does a vacuum reduce the explosive qualities of gunpowder, but any diminution in the pressure retards it. In 1855, Mitchell observed that fuses burned slower at high elevations; M. Frankland in 1861, at his laboratory, and then M. de Saint Robert on the Alps, made very exact determinations in this line. Under the pressures included between 722 mm. and 405 mm., according to the researches of M. de St. Robert, the rapidity of the combustion of powder under less than atmospheric pressure would be represented, for all practical purposes, by a formula such as $V = Ap^{\frac{2}{3}}$. A being a constant and p expressing the pressure. These results should be attributed to the greater or less rapidity with which the heated gases escape before having had time to heat the neighboring portions of the solid matter, which is equivalent to saying that the highly heated pressure diminishes the number of gaseous particles that come in contact, at

each instant, with the solid particles not yet ignited, and share with them their mechanical energy in a way so as to produce an equilibrium of temperature.

Whatever the pressure may be, the initial temperature of these particles is pretty much the same at constant volume, at least so far as it has not been modified by the chemical reaction. But if one operates under a constant pressure, it is otherwise, for the temperature is lowered in accordance with the expansion of the gases.

5. On the other hand, the quickness of combustion of powder increases with great rapidity, as soon as it attains the heavy pressures which are produced in cannon and in muskets; thus, for instance, Captain Castan reckons the rapidity of the combustion of powder in the bore of cannon of large calibre at 230 mm. per second, instead of 10 mm. in the open air.

6. The rapidity of combustion of other explosives has not been the subject of experiments as exact as those applied to gunpowder; but they suggest new

observations and a theory of an entirely different kind, as we shall immediately explain. However, we confine ourselves now to the statement that Piobert determined the rapidity of the combustion of gun-cotton (not compressed) as eight times that of gunpowder, a value which may be applied to the progressive combustion taking place without detonation.

7. These same studies were extended to explosive mixtures of gases. In 1867, M. Bunsen * determined the rapidity of combustion to be 34 m. per second for detonating gas (hydrogen and oxygen) and of one meter only per second for a mixture of equivalent parts of carbon monoxide and oxygen, these mixtures being taken at atmospheric pressures. He allowed the gas to issue through a small orifice, ignited the jet, and determined for what rapidity as a limit of flow the flame remained stationary at the opening without retreating into the interior. M. Mallard † has made similar

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* *Annales de Physique et de Chimie*, 4 Serie t. 14, p. 449.
† *Annales des Mines*, t. 8, 3e. livraison, 1871.

experiments in different mixtures of marsh gas or of illuminating gas and of air; he found that the rapidity of combustion, defined as above, rapidly diminishes in proportion as the amount of gas having no part in the combustion, increases. The maximum rapidity corresponding to 0.560 m. per second for a mixture of eight parts of air and one part of marsh gas by volume. It lowers itself to 0.04 m. with a mixture containing twelve parts of air to one of marsh gas. With illuminating gas and air, the maximum rapidity has almost reached double this amount. Mallard and Le Chatelier have restudied this question by other processes which have given them entirely different results according to the method of combustion. They will be referred to presently and the causes of these differences will be shown.

8. In reality the study of the new explosives, gun-cotton and nitro-glycerin, has lead to a better understanding of the knowledge of the methods of propagation of the chemical reaction in the midst of

a mass during combustion, and it has greatly modified the ideas which have been held on this subject. Formerly, when gunpowder was the only known explosive, its ignition only attracted attention, the effects of the explosion that followed not appearing dependent on the process of ignition. But nitroglycerin and dynamite have shown singular differences in this respect.

9. In order that these may be perfectly understood, it is necessary to first consider those phenomena of shock and other analogous causes capable of producing a deflagration.

The shock by itself will hardly induce the decomposition of a substance which absorbs heat, unless we refer to that of colossal masses animated by enormous mechanical energy, and concentrating all their action on a very small quantity of matter, something which is not easy to produce. For instance, the mechanical energy of a weight of 1630 kilograms falling from the height of a meter, would be necessary to decompose one gram of water, that is supposing that it would be possible to transmit to a gram of water, by any means, the entire amount of this mechanical energy.

On the other hand, if the substance in decomposing gives off heat, one would suppose that a limited mechanical energy would be sufficient to induce it to apply itself completely to a very small quantity of substance which it raises to temperature necessary to determine the reaction.

Thus, for instance, several violent strokes of a hammer on some powdered potassium chlorate, wrapped up in a sheet of platinum and placed on an anvil, is sufficient to produce traces of potassium chloride that are quite perceptible; while potassium sulphate will give no indications of decomposition under the same conditions. But it must be remembered that the decomposition of potassium sulphate into potassium sulphide and oxygen absorbs heat, while the decomposition of potassium chlorate into potassium chloride gives off heat, (11,000 calories for potassium chlorate).

10. This condition is, however, not sufficient for the shock to cause detonation. It is still necessary, that the mechanical energy developed by the decomposition of the first portions, should be communicated to adjoining portions, in such a way as to determine, step by step, the decomposition of the entire mass. The shock from the hammer, which is not sufficient to produce these conditions with pure potassium chlorate is, however, efficacious with nitro-glycerin. The fall of a weight 4.7 kgrams. from a height of 0.25 meter is sufficient to cause the explosion of a single drop of nitroglycerin occupying a surface of 2 cm. square.*

Nitro-glycerin mixed with infusorial earth constitutes dynamite, a substance which is but slightly sensitive to shock because the porous and cellular structure of the silica prevents the im-

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* Ch. Girard, Millot et Vogt, *Comptes Rendus des Seances de l'Academie des Sciences*, tome 71, p. 391.

mediate and local communication of the mechanical energy to a very slight quantity of nitro-glycerin separated from the rest. The explosion of gunpowder will cause the nitro-glycerin to detonate, but it will not lead to any explosion of dynamite, at least in the open air and in weak charges. But this inertia disappears under the influence of certain shocks, particularly violent, such as that of mercury fulminate. Thus the explosion of nitro-glycerin varies according as it is pure or mixed with some other body, whether it is effected by a simple shock, by the contact of a body in feeble ignition, or in strong ignition, or an ordinary match, or else by the contact of a strong mercury fulminate cap.

IV.

1. According to the process used for igniting, the dynamite may be decomposed quietly and without flame, or else it may burn with considerable vivacity, or else produce a detonation, properly

so called, which may be sometimes moderate, sometimes capable of dislocating rocks, sometimes even of destroying them *in situ*, and producing the most violent effects.

2. The substances, which are the cause of these last-named results, have been specially designated as *detonators*. Nobel was the first to observe these effects in nitro-glycerin (in 1864), and he then deduced a suitable process by which it could be made to detonate with certainty by means of a cap containing mercury fulminate. Gun-cotton does not show any less difference. Abel has published in this connection since 1868, many very curious experiments, which tend to establish a great diversity between the conditions of deflagration of this substance varying with the method of ignition.* Roux and Sarrau have generalized these phenomena by distinguishing what are known as *explosions of the first and of the second order*.

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* *Comptes Rendus des Seances de l'Academie des Sciences*, tome 69, p. 105–121. 1869.

3. However strange this diversity may appear at first sight, I nevertheless believe that the thermo-dynamic theories are capable of accounting for it, by a suitable analysis of the phenomena of the shock. In truth, the diversity of the explosive phenomena depends upon the rapidity with which this reaction propagates itself, and the more or less intense pressure which results from it.

Let the case be the simplset one, such as an explosion caused by the fall of a weight from a certain height. At first one would be disposed to charge the effects observed to the heat given off by the pressure due to the shock of the weight suddenly arrested. But calculation shows that the arresting of a weight of several kilogrammes, falling 0.25 to 0.50 m. in height, would not be capable of raising the temperature of the explosive mass more than a fraction of a degree, if the resulting heat was dispersed uniformly throughout the entire mass; this would not then attain an elevated temperature, that of 190 degrees, for instance, for nitro-glycerin, a temperature to which it appears necessary to suddenly raise the entire mass in order to produce an explosion.

It is by another mechanism that the mechanical energy of the weight which is transformed into heat becomes the originator of the observed effects. It is sufficient to admit that the pressures which arise from the shock exerted on the surface of the nitro-glycerin being too rapid to become uniformly dispersed throughout the entire mass, the transformation of the mechanical energy into heat takes place especially among the first layers reached by the shock. If it is sufficiently violent they may thus be rapidly elevated to 200°, and they will be immediately decomposed and produce a large quantity of gas. This production of gas is in its turn so violent, that the shocking body has not time to displace itself, and the sudden expansion of the gases of explosion produces a new shock probably more violent than the first on the layer situated below. The mechanical energy of this last shock is changed into heat in the layers which it reaches. It produces the explosion and this alternation between a shock, developing a mechanical energy which changes into heat and a production of heat which elevates the temperature of the heated layers up to the degree necessary for a new explosion capable of reproducing a shock; this alternation propagates the reaction, molecule by molecule, through the entire mass. The propagation of the deflagration takes place this way in consequence of phenomena comparable to those which produce a sonorous wave, that is to say, by producing a real explosion which advances with a rapidity incomparably greater than that of a simple burning provoked by the contact of a body in ignition and operating under conditions where the gases expand freely in proportion to their production.

4. This is not all. The reaction started by the first shock in a given explosive material is propagated with a rapidity

which depends upon the intensity of the first shock, provided that its mechanical energy changed into heat, determines the intensity of the first explosion, and in consequence that of the entire series of successive effects. For the intensity of the first shock may vary considerably, according to the method by which it is produced. The effect of a blow from a hammer may vary in its duration, according to the experiments of M. Marcel Duprez, from the one-one-hundredth to the one-ten-thousandth of a second, according as one strikes with a hammer having a flexible handle, or with a block of steel. From this it may be seen that the explosion of a solid mass or a liquid may develop itself according to an infinite number of different laws, each one of which is determined, all other things being equal, by the original impulse. The more violent the initial shock, the greater will be the resulting violence of the decomposition and the greater will be the pressures which are exerted during the entire course of this decomposition. One and the same explosive substance may produce very different effects according to the method of ignition.

5. The effects likewise differ as the substance is pure or mixed with a foreign substance, and in accordance with the structure of the latter. This feature is shown by dynamite, a mixture of nitroglycerin with silicon, which has lost the greater part of its sensitiveness to an ordinary shock, but remains explosive to the shock of a ball, and above all, to that of mercury fulminate.

The addition of a few per cent. of camphor to dynamite will still further diminish its explosive qualities to such an extent even, that it will no longer detonate except with strong fulminate caps.

6. Gun-cotton, impregnated with water, or with paraffine, becomes likewise insensible to a shock; for its detonation, then, it requires the use of a small supplementary cartridge of dry gun-cotton, itself charged with fulminate.

If several per cent. of camphor are mixed with nitrated cellulose, its susceptibility to explode by a shock is almost completely destroyed, at least at ordinary temperatures; to such an extent that this mixture forms a substance which is used to-day for many purposes in the arts under the name of *celluloid*.

7. Gum dynamite, which results from the combination of nitro-glycerin with gun cotton, sometimes with camphor added, also forms an elastic mass which is only slightly sensitive to shock, and which also requires an auxilliary cartridge of dry gun-gotton, itself charg ed with fulminate.

8. The change brought about in the explosive power of similar substances, by the addition of camphor and resinous substances, is the result of a modification brought about in the cohesion of the mass. This has acquired a certain elasticity and a solidity of parts, in consequence of which the initial shock of the detonator propagates itself at the beginning through a much greater mass. Besides a portion of the effects are expended in the work of rending and sep-

aration, but there still remains the smaller portion which is capable of producing heat in the parts directly struck, this heating, however, being dispersed through a larger mass. Therefore, a sudden elevation of temperature at one spot, capable of producing successive chemical and mechanical action can only be produced with difficulty; it requires the employment of a much greater weight of the detonator. This follows directly from the preceding theory.

9. But camphor, on the contrary, should not produce, and does not, as experience goes to prove, any specific action on a discontinuous powder, such as the potassium chlorate powders. It is on this account that it is necessary to take into consideration that frozen dynamite jelly possesses a sensibility to shock comparable to that of nitro-glycerin if the solidity of the parts have become destroyed by crystallization.

10. The importance of *caps* may be clearly seen from the foregoing. Heretofore they have been regarded simply as

agents for communicating the ignition to the powder. In reality, these caps, when they are of sufficient size, regulate by their nature the character of the initial shock, and in consequence the character of the entire explosion. In this case they are true *detonators*. Mercury fulminate is used for this purpose particularly, on account of its being most powerful, that is to say, its shock is more violent and more sudden than that of any other substance, which is explained by the greatness of the pressure which it develops by detonating within its own volume (nearly 40,000 atmospheres).

We have given above a certain number of characteristics relative to the special influence of caps. We shall return to this subject.

V.

§ 4.—*Burning and Detonation.*

1. The term *inflammation* is specially given to progressive combustion, the expression *detonation* being reserved for

rapid and almost instantaneous combustions. Hence we obtain the distinction proposed by M. Sarrau between *detonations of the first order*, such as those of gunpowder, whose detonation is the starting point of the series of burnings, and *detonations of the second order*, or detonations proper, such as those of nitro-glycerin induced by a powerful cap of mercury fulminate. However, the known facts do not, in my opinion, oblige us to admit of a difference in nature or of a sharp line of demarcation between the two varieties of phenomena. They tend rather to cause them to present an indefinite variety, included between the two extreme limits, as follows:

First. *The detonation of the explosive in its own volume*, reaching the maximum of temperature and of pressure, and in consequence, the maximum of speed of which the chemical reaction taking place under these conditions is susceptible. This detonation is specially induced by a very quick shock. The gases formed at the point where the shock is produced has not, so to speak, the time to be displaced, and so to communicate their mechanical energy to the parts in contact; the action is thus propagated throughout the entire mass with a certain degree of regularity. It is to this order of detonation that the rapidity of propagation, which is so different from the combustion of gunpowder, belongs. This last has been measured in comparison with dynamite and compressed gun-cotton. For instance, Austrian artillerists have noticed a rapidity of over 6,000 meters a second when a cylinder of dynamite 67 meters long was detonated. Colonel Sébert has observed velocities of 5,000 to 7,000 meters in gun-cotton, powdered and compressed in long tubes of lead. Further on it will be seen that I myself measured with M. Vieille velocities of several thousands of meters per second in mixtures of detonating gases taken at the ordinary pressure and contained in tubes of iron, of lead, or even of rubber.

Second. *Progressive inflammation* propagating itself from particle to particle under circumstances where the cooling due to external agents lowers the temperature to the lowest degree compatible with the continuation of the reaction.

It is to this order of burning that we refer the rapidity of combustion of the detonating gases, as measured by Bunsen. In the case of solid or liquid explosives, the propagation of a simple inflammation is rendered more difficult than otherwise by the movements of the gases which expand to a considerable extent around the point which is set on fire, instead of acting in an equal volume or in one slightly different from that of the primitive body. Their temperatures are thus reduced by distribution through a greater mass of matter. The heat is frequently found to be dissipated by the gases without giving rise to a total combustion or even inducing any change. This is particularly the case with explosives which are not confined in an envelope to concentrate the action of the gases and give them a common resultant.

This is the case with the nitro-glycerin which is found unaltered in the vicinity during progressive explosions; such is likewise the case with dynamite that is laid along the ground in a thin layer. Damp gun-cotton that is not inflammable when cold, also furnishes a number of illustrations of this dispersion, resulting from the use of an insufficient detonator. It is in consequence of this reaction of the gases that it is deemed advisable to prevent the simple burning of dynamite in cartridges from preceding the action of the fulminate.

2. Between these two limits there is observed an entire series of intermediate stages of an unlimited number, as is shown by the different methods of burning of dynamite, and the influence of tamping which allows the transformation from burning into a real detonation, if the tamping is sufficiently resisting. Finally, we may cite the inequality of the effects produced by the successive explosions of charges of the same agent, which detonate by influence within limited dis-

tances beyond which the explosion will not propagate itself.

3. We must also refer to the chemical phenomena. That of decomposition prevails when the explosive substance contains sufficient oxygen for complete combustion as occurs for nitro-glycerin and nitro-mannite; besides it is necessary that this total combustion shall have actually taken place, which does not necessarily happen, especially in slow burnings performed at a low temperature.

4. But it often happens that the oxygen is insufficient, or that the first reaction gives rise to a wasteful expenditure of this oxygen, as is the case when nitroglycerin burns slowly, with the production of nitrous vapors and of fixed or gaseous products of incomplete combustion. Under these circumstances the possible decompositions are numerous; their number depends on the temperature, on the pressure, and on the rapidity of the heating. We have already remarked upon this in the case of ammonium nitrate; it may be observed in general in

organic substances, which may be decomposed by heating. (*Essai de Mecan. Chimique*, t. II., p. 45.)

5. Among these decompositions those which develop the most heat are those which produce the most violent explosive effects, other conditions being equal. This fact is evident when the volume of gas (reduced at 0° and 0.760) reaches in the same time its maximum value. But it is also verified in other cases, the dissociation giving rise always to a diminution of pressure, as I have shown elsewhere. On the other hand, this fact does not obtain as a general thing in reactions which are produced at the lowest possible temperature. If then, the explosive body receives in a given time a quantity of heat insufficient to carry the temperature up to a degree, which corresponds to the most violent reaction, it will experience a decomposition capable of giving off less heat, or even of absorbing heat; and it is capable of undergoing complete decomposition without

developing the most energetic explosive effects.

The opposite will take place if the body is quickly heated to the temperature corresponding to the most energetic reactions.

6. Finally the multiplicity of the possible reactions carries with it a series of intermediate effects, and this all the more, because, according to the mode of heating, it may happen that several decompositions will follow each other progressively. This succession of decompositions gives rise to effects which are very complicated, as has been noticed by M. Jungfleisch, when the first decomposition instead of producing a total elimination of the decomposed portions (changed into gaseous or volatile substances) produces a division of the primitive substance into two parts: the one gaseous, which passes away; the other solid or liquid, which remains exposed to the action of the heat resulting. The composition of this residue remains no longer the same, as, for instance, with nitro-

glycerin which first loses a portion of its oxygen in the form of nitrous vapors, and thus the results of its successive decomposition may become completely changed.

7. Such are the causes, some chemical, others mechanical, through which nitro-glycerin and compressed gun-cotton produce all of these different effects, according as they are ignited by the aid of a body in feeble combustion, or by a flame, or by an ordinary cap, or else by means of a cap charged with mercury fulminate.

For example, M. M. Roux and Sarrau have found that the charge necessary to break a shell, other things being equal, will vary in the inverse ratio of the following numbers, these numbers being referred to gunpowder, taken at unity—

	Detonation.		Inflammation.
Nitro-glycerin..........	10.0	.	4.8
Compressed gun-cotton	6,5	.	3.0
Picric acid............	5.5	.	2.0
Potassium picrate......	5.3	.	1.8

The weight of the breaking charge, in the case of gunpowder itself, under the influence of nitro-glycerin primed with fulminate, is capable of being reduced in the ratio of 4.34 to 1.

This inequality in the force of different powders is partially attributed to the cooling which is effected by the walls, during a slow reaction, and also in part to the changed chemical condition.

8. The diversity is less marked with the non-compressed gun-cotton, because the influence of the initial shock is exerted on a smaller quantity of matter, and above all, because the propagation of the successive reactions in the mass develops their initial pressures less, and a less direct transformation of mechanical energy into heat is transmitted to the explosive body, on account of the air which is interposed, and in consequence the explosive wave can hardly be generated.

Compressed gun-cotton is not so compact as nitro-glycerin, because of its structure; the pressures due to shocks might be sensibly weakened by the existence of interstices. Gun-cotton also detonates with more difficulty than nitro-glycerin. Nitro-glycerin will detonate by the fall of a weight from an insignificant height, that is, provided a cap charged with gun-cotton or a mixture of fulminate and of potassium chlorate, etc., is used; while on the other hand, gun-cotton does not explode by the influence of nitro-glycerin, nor by the influence of a mixture of fulminate and of chlorate. It requires the more violent shock of pure mercury fulminate. Besides this, it is less efficacious if it is used unenclosed than when confined in a thick envelope of copper or tin plate; it is less powerful in an envelope of paper or tin-foil than it is when wrapped in copper; it is still less powerful if the cap is not in direct contact with the gun-cotton. Finally, if it is placed in the tube of a feather its effect will be *nil*. Nitro-glycerin does not detonate so well when exposed to the influence of a fulminate primer, if it becomes ignited before the explosion of the fulminate, this preliminary ignition having the effect of producing a certain vacuum between the two.

The lack of immediate contact between dynamite contained in cartridges and the fulminate cap is objectionable for the same reason, the shock being weakened in part by the interposed air. The greater sensitiveness to the action of the fulminate of dynamite which contains liquid nitro-glycerin over that which contains frozen nitro-glycerin may also be explained as due to the lack of homogeneity of the frozen dynamite in which the nitro-glycerin is partly separated from the porous silica in consequence of its solidification.

9. All these phenomena may be explained by the greater or less force of the initial pressures, and by their more or less rapid development; that is to say, by the conditions which regulate the mechanical energy transformed into heat within a given time, in the midst of the first layers of the explosive substance reached by the shock.

The quantity of mechanical energy

thus transformed depends first upon the brusqueness of the shock and also upon the amount of work which it may produce; these are factors which vary with every explosive material. For instance, it is not always that the most sensitive caps are those which produce the most instantaneous explosion. M. Abel has observed that nitrogen chloride is not particularly adapted for igniting gun-cotton; nitrogen-iodide, so sensitive to the least friction, remains entirely powerless to explode gun-cotton. Now, nitrogen chloride is precisely the one among these explosive bodies that we are at present discussing, which develops the least heat and in consequence the least work for a given weight. We conclude, then, that it cannot be advantageously employed for caps or priming. As to nitrogen-iodide, according to the analogies drawn from the iod substitution compounds (see *Annales de Chemie et de Physique*, 4 series, vol. 20, p. 449) its explosion should develop still less heat and work for the same weight than the nitrogen chloride. Its weakness is therefore easy to comprehend.

VI.

1. The phenomena which we have described belong to solid or liquid explosives, but the gaseous compounds and the detonating mixtures of gases give similar results, and these throw a still greater light on the theory. In reality the chemical transformation of such a gaseous mixture may act with very different rapidities according to the mode of propagation of the decomposition or of the combustion.

2. Let us begin with a compressed gas formed with the absorption of heat according to its elements, such as hypochlorous anhydride ($Cl_2 + O = Cl_2O$ absorbs $-$ 7.6), acetylene ($C_2 + H_2 = C_2H_2$ absorbs$-$61.5) or cyanogen ($C_2 + N_2 = C_2N_2 - 74.5$.

Such a gas is decomposed in the inverse proportion to the liberation of heat. This, in effect, is what we obtained with hypochlorous gas, heated below 100°

or traversed by an electric spark, or placed in contact with a body in ignition; the gas detonated at once, reproducing chlorine and oxygen. But it is not the same with acetylene nor with cyanogen. These gases neither detonate by the influence of heating nor by the influence of the electric spark, although they are decomposed by them, little by little, and without exploding. On the other hand, I have found that a quick shock of mercury fulminate will cause them to detonate rapidly with considerable flame, and separation of their elements, carbon and hydrogen in the case of acetylene, and carbon and nitrogen in the case of cyanogen. The experiments have recently been described.*

3. The explosive mixtures formed by the union of oxygen with a combustible gas, may also burn with extremely varying rapidities, according to the method of the propagation of the chemical reaction.

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* See *Comptes Rendus*, 93, p. 240.

We have cited the experiments of M. Bunsen who thought it possible to fix the rapidity of combustion of a mixture of hydrogen and oxygen gas, in equivalent proportions, at 34 meters per second, and that of a mixture of carbon monoxide and oxygen at only a meter. These experiments were based on the retrogradation of the flame back into the mixture, while flowing out into the atmosphere through a narrow opening. Having recently undertaken these experiments with M. Vieille under different conditons, we have observed rapidities incomparably greater. Our method of operation was as follows:

On each occasion we filled, under atmospheric pressure, with an explosive mixture, an iron tube 5 meters long, having an internal diameter equal to 8 mm., capable of being sometimes kept open and sometimes closed at its extremities, or else a lead tube 40 meters in length, or sometimes a thick india-rubber tube 40 meters long. By means of a special arrangement we were able to register the passage of the explosive wave, first at the beginning of the tube, then further on, and finally at the end of the tube,* and also we were able to measure the time elapsing between these different passages. These experiments were made with tubes which were sometimes opened at one extremity and sometimes closed; on some occasions they were placed horizontally, and on others they were arranged vertically, and under different pressures. They proved to us that the detonation is propagated with a rapidity equal to thousands of meters per second, as well for the mixture of hydrogen and oxygen as for the mixture of carbon monoxide and oxygen.

4. The difference between these results and those which were obtained by M. Bunsen may be explained by the variance in conditions. The gases burned in the earlier experiments were cooled by contact with the air, and the explosive wave was not produced. The difference between the two kinds of combustion ap-

* *Comptes Rendus*, 93, p. 19.

peared analogous to that which exists between the simple burning of explosive substances, an operation in which the movement of the different particles takes place confusedly and in an independent manner, and their sudden detonation, provoked by a fulminating cap, an operation in which the movements become co-ordinated. Hence the effects of temperature and of pressure attain their maximum, and are propagated with an incomparably greater rapidity. Some of these observations made with the fire-damp of mines seems to bear an analogous interpretation.

5. The characteristic feature of this order of phenomena is the production of an explosive wave, that is to say, of a certain regular surface where the transformation is produced and which brings about a similar state of combination, of temperature, of pressure, etc. This surface, once produced, propagates itself layer by layer throughout the entire mass, in consequence of the transmission of successive shocks of the gas-

eous molecules carried to a vibratory condition more intense in consequence of the heat given off in their combination and transformed *in situ*, or more exactly with a relatively feeble displacement. Analogous phenomena may be developed with solid and liquid explosives in conformity with what has been said above.

6. These effects are comparable to those of a sound wave; but, however, with this important difference, that the explosive phenomena does not reproduce itself periodically, that is to say, it starts a single and characteristic wave, whereas the phenomena of sound is reproduced by a periodical succession of equal waves.

There is, moreover, this important difference that the mechanical energy of a system of molecules, whose association forms the sound wave, remains sensibly constant during the propagation of the wave, and that it is slight, while the mechanical energy of the system of molecules which constitutes the explosive wave is enormous, and that it begins at once by growing and tends towards a maximum, which is determined by the very highest temperature that the system can reach due to the chemical transformation actually realizable. In fact this maximum is never reached, in consequence of the conditions of cooling, but it is more nearly approached as the reaction is more rapid, and is carried on in a medium more condensed and on a greater mass.

7. The propagation of successive shocks between the ultimate molecules of bodies leads us to push further the comparison of the mechanical effects and the thermal effects which are developed simultaneously. In reality the mechanical energy communicated to this order of molecules by the chemical combination is nothing else than the heat itself given off in the reaction, and the pressure exerted on the molecules themselves and on the walls of the vessels, is the immediate phase of the transformation according to present theories. We have reached, therefore, a point where the two orders of ideas tend to confound themselves.

8. It follows from these explanations that the rapidity of the propagation of the explosion becomes comparable to the rapidity of sound, which is also propagated in virtue of an undulatory movement, the rapidity of these two movements being of the same order as the rapidity of translations of the gaseous molecules.

9. It is possible to define this point of view by observing that the rapidity of the translation of the gaseous molecules is equal, according to the formulas of M. Clausius to 29.354 meters $\sqrt{\frac{T}{p}}$ per second. T in this instance represents the absolute temperature $(273+t)$, p the density of the gaseous mixture in terms of that of air. Let $T=3000°$, a temperature whose development* may be admitted in the gaseous mixtures which we are considering, taken at the normal pressure. The actual rapidity of the translation of the gaseous molecules would be included between 1,300 meters

* *Ann. de Chem. et de Phys.*, 5 Series 12, 309.

and 1,600 per second, according as one operates on carbon dioxide or on a mixture of carbon monoxide and oxygen, or on a dissociated mixture containing these different compounds. It would be included between 2,000 and 2,500 meters per second for steam or its constituents. These figures may furnish the first term of the comparison, though we must not forget that explosive phenomena are more complex than a simple movement of translation, or even than the propagation of a sound wave.

VII.

Explosions by Influence.

1. Thus far we have regarded the development of the explosive reactions either from the point of view of their duration in an homogeneous system in which all the parts are maintained at the same temperature, or else from the standpoint of their propagation in a system equally homogeneous, to which fire is ap-

plied directly by means of a body in ignition or else by a violent shock. In these later years, however, the study of explosive substances has revealed the existence of another method of propagating the reactions in an explosive center, this propagation taking place at a distance and by the intermediation of the air or certain solid bodies which do not themselves participate in the chemical change.

We shall now speak of what are called explosions by influence, whose existence was formerly suspected from certain known facts relative to the simultaneous explosion of several buildings separated by considerable space from each other, as in catastrophes occurring in powder mills. Attention has been specially directed to this class of phenomena by the study of nitro-glycerin and gun-cotton.

2. We will begin by giving the most important characteristic facts. A dynamite cartridge made to detonate by means of a fulminate cap causes the ad-

joining cartridges to detonate, not only by contact and by direct shock, but even from a distance. In this way an indefinite number of cartridges, arranged in a regular course, may be made to detonate.

3. The distances to which the explosion may be propagated are relatively great. Thus, for instance, with cartridges contained in rigid metallic envelopes and placed on a resisting soil, the detonation produced by 100 grams of Vonges dynamite (75 per cent. nitro-glycerin, and 25 per cent. randanite, that is to say, very finely divided silica) communicates itself 0.3 meters of distance, according to the experiments of Captain Coville. D being equal to the distance in meters, and C the weight of the charge in kilograms, the experiments of this officer show that $D=3.0C$.

When the caps were laid on a rail, D was found to be equal to 7.0C.

On soft or ploughed-up earth the distances, on the contrary, are less.

When a cartridge is suspended in air

there is no detonation by influence, perhaps because the cartridge not being fixed can recoil freely, which diminishes the violence of the shock. Nevertheless, there are experiments which show that the air suffices for the transmission of the detonation by influence, although with greater difficulty and requiring a greater mass of the explosive.

With a dynamite less rich in nitroglycerin (55 per cent. of nitro-glycerin and 45 per cent. of the argillaceous ashes of boghead coal), contained in similar cartridges, and placed along the ground, the experiments of Captain Pamard have given the smallest distances: $D=0.90C$. If metallic envelopes having less resistance are used, the distance at which the explosion is propagated is likewise diminished. Dynamite simply spread along the ground ceases to propagate the explosion. The experiments performed in Austria have given similar results. They have shown that the explosion is communicated either in the free air with intervals of 4 cm., or else through pine boards 18 mm. thick. In a lead tube with a diameter =0.15 meters and a meter in length, a cartridge placed at one extremity has caused the detonation of a cartridge at the other end. The explosion is still better transmitted through tubes made with wrought iron. The couplings of the tube diminish their aptitude for transmission.

4. An explosion which is propagated in this manner will go on weakening itself from cartridge to cartridge, and even change its character. Thus, according to the experiments made by Captain Müntz at Versailles, in 1872, a first charge of dynamite, exploded directly, excavated a funnel-shaped hole in the ground with a radius of 0.30 meters ; the second charge, detonated by influence, produced an opening of only 0.22 meters ; the effect of the detonation was then reduced. This reduction should manifest itself towards the limit of the distance at which the influence ceases. In the same way four tin sieves were taken and located

40 mm. apart, a small cylinder of guncotton was placed against each of them and the entire affair arranged on a board. 15 mm. in front of the first sieve a similar cylinder was detonated. All of the cylinders detonated, but a progressive diminution was observed in the indentations produced in the board below each cylinder. According to these facts the propagation by influence depends at the same time on the pressure acquired by the gas, and on the nature of the support. It is not even necessary that it should be rigid.

5. Finally, in operating under water at a depth of 1.30 meters, a charge of 5 kilograms of dynamite brought on an explosion of a charge of 4 kilograms, situated at a distance of 3 meters. The water then transmits the explosive shock, at least to a certain distance, as does a solid body. This transmission is so violent that the fish are killed in ponds within a sphere of a certain radius by the explosion of a dynamite cartridge, a process which is frequently employed

to fish a body of water, but which is objectionable as depopulating the stream.

6. Similar experiments have been made by Abel, with compressed gun-cotton. According to his observations the explosion of the first block determines that of a series of similar blocks. The propagation under water has likewise been studied; the explosion of a torpedo charged with fulminating cotton caused the detonation of adjoining torpedoes placed within a certain radius of activity. The sudden pressures transmitted by the water when measured by means of the compression of lead at different distances, such as 2.50 m., 3.50 m., 4.50 m., 5.50 m., go on decreasing, as would be expected. Besides, experiment has shown, that the relative position of the charge and of the "crusher" is of no consequence, which is in harmony with the principle of equal transmission in all directions of hydraulic pressures.

7. Explosions of fulminating substances, which are rapidly propagated to a great number of caps, belong to this

same order of explosions by influence. We have previously cited the explosion in the Rue Beranger. The experiments which M. Sarrau made on that occasion showed that caps of the description which produced this catastrophe may be successively burned in a fire without giving rise to a general explosion; whereas the explosion of a few of these same caps, each containing 10 milligrammes of explosive material, if it is provoked by a rapid pressure, determines by influence the explosion of the adjoining packages, even when they are not contiguous and are situated at a distance of 15 centimeters apart. A general explosion may thus easily be produced by influence.

8. It follows then from these facts, and especially from the experiments made under water, that the explosions by influence are not due to inflammation, properly so called, but to the transmission of a shock arising from the enormous and sudden pressures produced by the nitro-glycerin or the gun-cotton.

Let us enlarge upon this explanation; it is the same fundamentally as that which we have already shown as accounting for the influence of the shock which determines the direct detonation of explosive substances.

9. In an extremely rapid reaction, the pressures may approach to the limit which corresponds to the matter detonating in its own volume, and the commotion due to the sudden development of almost theoretical pressures can be propagated both through the ground and supports as intermediary or through the air itself, projected *en masse*, as has been shown by the explosion of certain powder factories and of gun-cotton magazines, and even by some of the experiments with dynamite and compressed gun-cotton. The intensity of the shock propagated either by a column of air or by a liquid or solid mass, varies with the nature of the explosive body and its mode of inflammation; it is of greater violence according as the length of the chemical reaction is shorter and develops

more gas, that is to say, a higher initial pressure, and more heat, that is to say, work, for the same weight of explosive material.

10. This transmission of a shock is conveyed better by solids than by liquids, better by liquids than by gases; with gases it becomes better, as they are more compressed. Through solids it is better propagated according to their degree of hardness, iron transmitting it better than earth, and hard ground better than ploughed soil.

All breaks of continuity in the transmitting material tend to weaken it, especially if a softer substance is interposed. Thus it is that the use of a tube, made from a goose quill, as a receiver stops the effect of mercury fulminate, while a tube or a capsule of copper transmits this effect in all its intensity.

The explosions by influence are the better propagated in a series of cartridges according as the envelope of the first detonating cartridge is the more resisting, which allows the gases to attain a greater pressure before the covering is destroyed.

The existence of an empty space, that is to say, filled only with air, between the fulminate and the dynamite, on the other hand diminishes the violence of the shock transmitted, and in consequence that of the explosion; generally the effects of breaking powders are lessened when there is no contact.

11. To form a full conception of the transmission of sudden pressures which produce shock by the supporting medium, it is desirable to recall this general principle, in virtue of which in a homogeneous mass, pressures are transmitted equally in all directions and are the same on a small element of surface whatever its position. Detonations produced under water with gun-cotton show that this principle is equally applicable to the sudden pressures which produce the explosive phenomena. But it ceases to be true when one passes from one medium to another.

12. If the inert chemical matter which transmits the explosive movement is fixed in a given situation on the surface of the ground, or better, on the surface of the rail on which the first cartridge was placed, or better still, held by the pressure of a mass of deep water, in the midst of which the first detonation is produced, the propagation of the movement in this matter will hardly be able to take place except under the form of a wave of a purely physical order, and consequently of an essentially different character from the first wave of a chemical and physical order simultaneously developed in the explosive body itself. This new wave propagates the concussion away from the explosive center, all around it, and with an intensity which decreases inversely as the square of the distance. Even in the neighborhood of the center, the displacements of the molecules may break the cohesion of the mass and disperse it, or crush it by enlarging the chamber of explosion, if the operation is conducted in a cavity. But

a very short distance (the magnitude of which depends on the elasticity of the surrounding medium) these movements, confused at the beginning, arrange themselves in such order as to produce a wave, properly so called, characterized by compressions and sudden deformations of the material, the amplitude of these oscillations depending upon the magnitude of the initial impulse. They move with a very great rapidity, and preserve their regularity up to the point where the medium is broken. Then these compressions and sudden deformations change their nature and are transformed into a movement of impulse, that is to say, they reproduce the shock. If then they act on a new cartridge they may determine its explosion; the shock will be otherwise weakened by the distance, and in consequence the character of the explosion may be modified. The effects diminish in this manner up to a certain point, from which the explosion ceases to produce itself.

When this occurs on a second cartridge the same series of effects will be produced from the second to the third cartridge; but they depend on the character of the explosion of the second cartridge. And thus it goes on.

13. Such is the theory that appears to me to explain explosions by influence and the phenomena which accompany them. It depends, definitely, on the production of two orders of waves; one series represents the explosive waves, properly so called, developed in the midst of the matter which detonates, and consists of a continually reproduced transformation of the chemical actions into thermal and mechanical actions, which transmit the shock to the support and to the contiguous bodies; the other is a purely mechanical and physical series, which transmits equally the sudden pressures all round the center of the concussion to the adjoining bodies, and by a singular circumstance to a new mass of explosive material.

14. A theory differing from this was originally proposed by Abel. It is the

theory of *Synchronous vibrations*, to which we shall now direct our attention. According to this English savant, the originating cause of the detonation of an explosive lies in the synchronism, between the vibrations produced by the body which provokes the detonation, and those which the first body would produce in detonating, precisely as a violin string resounds at a distance in unison with another vibrating chord.

Prof. Abel has cited the following facts in support of his theory. To begin with, the detonators appear to differ with each variety of explosive. For instance, nitrogen iodide, so susceptible to shock or friction, cannot cause the detonation of compressed gun-cotton. Nitrogen chloride, so easily exploded will not produce the same detonation, except when ten times the weight of the necessary fulminate is used. In the same way nitro-glycerin will not produce a detonation of gun-cotton in sheets on which is placed the case containing the nitro-glycerin. In this way nitro-glycerin up to 23.3 grams can be detonated without effect. On the other hand, the inverse influence is proved; 7.75 grams of compressed gun-cotton having caused the detonation at a distance of 25 mm. of nitro-glycerin wrapped up in an envelope of thin sheet iron. A cap filled with a mixture of potassium ferrocyanide and potassium chlorate, likewise, (according to Brown) will not detonate gun-cotton. Finally, a cap consisting of a mixture of mercury fulminate and potassium chlorate, should be used of much heavier weight than if it be filled with the pure fulminate, (according to Trauzl). Nevertheless, the heat given off by the same weight is greater by one-fifth than that with the first mixture.

15. Messrs. Champion and Pellet have brought to the support of this ingenious hypothesis the following experiments: they attached to the strings of a double bass particles of nitrogen iodide, a substance which detonates on the slightest friction. Then they made the strings of a similar instrument vibrate at a short

distance off; a detonation was produced, but only for sounds higher than a certain note, which corresponds to 60 vibrations per second. They also took two conjugate parabolic mirrors placed 2.5 meters apart and they arranged along the line of foci at different points several drops of nitro-glycerin or of nitrogen-iodide, then they detonated at one of the foci a large drop of nitro-glycerin; they observed that the explosive substances placed in the conjugated foci detonated in unison to the exclusion of the same substances placed at other points. A layer of lamp-black placed on the surface of the mirrors was designed to prevent the reflection and the concentration of the heat rays.

16. As yet none of the experiments appear to me to be conclusive, and several of them seem even to be formally opposed to the theory. We shall begin by observing that the characteristic feature of a given musical note, capable of determining each variety of explosion, has never been established; it is only below a certain note

that the effects cease to be produced while they take place by preference, whatever the explosive bodies may be, by the action of the most acute notes. Besides, these effects cease to produce themselves at distances which are incomparably less than the resources of the chords in unison, which goes to prove that the detonations are functions of the intensity of the mechanical action, rather than of the character of the determining vibration. Similarly, the detonation ceases to be produced when the weight of the detonator is too slight, and in consequence when the mechanical energy of the shock is weakened. Nevertheless, the specific vibratory note which determines the explosions should always remain the same. For instance, cartridges filled with 75 per cent. of dynamite cease to detonate when the capsule contains a weight of fulminate less than 0.2 grams; the detonation only being assured in all cases by the regulation weight of one gram. This confirms the existence of a direct relation between the character of the detonation and the intensity of the shock produced by one and the same detonator.

If it is true that gun-cotton will cause the nitro-glycerin to detonate in consequence of the synchronism of the vibration communicated, then we do not understand why the reciprocal action does not take place, while the absence of reciprocity can be easily explained by the difference of the structure of the two substances which play so important a part in the transformation of the mechanical energy into work.

17. This same diversity of structure and the modifications which it introduces into the transmission of the phenomena of shock and the transformation of mechanical energy into thermal energy, may be called upon to explain the facts observed by Abel.

The difference between the energy of pure fulminate and of the fulminate mixed with potassium chlorate is no less easily explained; the shock produced by the first body being sharper on account of the absence of all dissociation of the product (which is no other than carbon monoxide), this absence should be contrasted with the dissociation of carbon dioxide formed in the second case. Perhaps, also, the formation of potassium chloride disseminated through the gas produced, with the concurrence of potassium chlorate weakens the shock, just the same as silicon does in the case of dynamite.

18. All the effects observed with nitrogen-iodide may be explained by the vibration of the supports and by the effects of rubbing which results therefrom, this substance being particularly sensitive to friction.

19. The experiment with the conjugate mirrors may also be easily explained by the concentration in the focus of the movements of the air, and therefore of the mechanical effects which result.

20. Besides, M. Lambert has proved by experiments made for the commission on explosive substances, that in the explosion of dynamite cartridges in tubes

of cast iron of large diameter, regarded from the standpoint of detonations by influence, there does not appear to be any difference between the ventral segments and the nodes characteristic of the tube.

21. Desiring to clear up this entire question by removing it from the influence of the supports and of the diversity of cohesion and physical structure of solid explosive substances, I undertook a series of special experiments on the chemical stability of matter in sonorous vibration and especially on that of gaseous bodies such as ozone, hydrogen arsenide or liquids, such as hydrogen peroxide, and persulphuric acid, all of these bodies being selected from among those which decompose or change spontaneously, at ordinary temperatures with the disengagement of heat, precisely as explosive substances do. The description of these experiments may be found in the *Comptes Rendus* or in the *Revue Scientifique*, May, 1880.

They lead to the conclusion, that substances which are transformable with the disengagement of heat, are stable under the influence of sound waves, while they are decomposed under the influence of ethereal vibrations. This diversity in the mode of action of the two classes of vibrations is not surprising when we consider that the most acute sonorous vibrations are incomparably slower than the luminous or thermal vibrations.

22. Hence, it appears certain that the propagation of explosions by influence is not made in virtue of an undulatory movement, which is a complex motion of a chemical and physical order in the midst of the explosive substance which is decomposed, while it is purely physical in the midst of intermediary substances which suffer no decomposition. But that which distinguishes this sort of movement of the vibrations, properly so called, is, first of all, its extreme intensity, that is to say, the magnitude of the mechanical energy which it transmits; it is also the unique character of the explosive wave

which is propagated in contra-distinction with the multiplicity of successive sonorous waves. Finally it is essential to observe that the explosive material does not detonate because it transmits the movement, but on the contrary because it arrests it, and because it transforms on the spot the mechanical energy into thermal energy, capable of suddenly raising the temperature of the substance up to the degree which will produce its decomposition.

A SHORT

HISTORICAL SKETCH

OF

GUNPOWDER.

— BY —

KARL BRAUN.

A Short Historical Sketch of Gunpowder.

THE question, "Who discovered gunpowder?" is usually answered to-day *unisono:*

"Berthold Schwarz, the Freiburg monk."

So our youth has been taught for two generations, and this is quite enough to make any doubt of this assumed fact appear as idle folly.

Nevertheless doubt is justified. The contemporaneous writers, the authors of the middle and of the latter half of the fourteenth century, knew nothing of the discovery of the monk of Freiburg. The name of Berthold Schwarz is first mentioned long after "Büchsen" and "Katzen" (small cannon or mortars) were used in firing, and after a "Katzenstadl," *i. e.*, a gun-foundry, as well as an arsenal existed in Augsburg, for instance.

But even those who grant Schwarz the

honor of being the first to make use of the preparation of gunpowder in Germany, and to spread the knowledge of its use, deny him part of the merit of the discovery. They assert that he too belongs to the great number of those "who did *not* discover gunpowder;" at all events he could not have taken out a patent on his "invention," for it had been in use for centuries. The Chinese had been long acquainted with it; traces of it are found among the Saracens and the Byzantines; it may be assumed, say they, that the discovery is derived from the Chinese, and has passed by various, no longer accurately determinable, steps, to the Byzantines, and through them has arrived in Germany; although the Byzantine or "Greek fire" is not identical with modern gunpowder, it is of earlier date, and the latter bears the same relation to the former that an amendment bears to the principal motion, or an additional or improvement pattern to the main patent.

Occupied with these doubts, I find in

the "Chronicles of Augsburg," composed by the learned Clemens Jager, about the middle of the sixteenth century, the notice that *a Jew, named Typsiles, discovered gunpowder in the year 1353, in Augsburg, and from Augsburg the preparation of gunpowder, its application to military purposes, and the manufacture of fire-arms, spread throughout Germany and over the rest of Europe.*

True, the chronicler Clemens Jager, writes two hundred years after the discovery and the propagation of gunpowder manufacture in Europe, and cannot therefore speak from personal observation or the observation of his contemporaries. But the same is true of the warranters and witnesses of the patent of the monk of Freiburg. Clemens Jager is, however, to be regarded as an earnest and authentic writer, who has studied his sources carefully. We are compelled to believe that, to make such an assertion with such apodictic certainty, he must have had his good sources and grounds therefor, and that he could assume belief and agreement in his assertion from his fellow-citizens in Augsburg, who were acquainted with his sources, and instructed by the traditions of their forefathers on the subject. Indeed, his statement not only remained uncontradicted at the time, but was confirmed and repeated by other chroniclers and other authors of later date.

We may therefore assume as authentic that it was believed in Augsburg, in the sixteenth century, that the discovery or re-discovery of gunpowder by the said Typsiles took place within the walls of that good city.

I acknowledge that this view is founded on a legend as well as that which asserts the authorship of Berthold Schwarz. In this respect one has not much preference over the other. We also know little more of Schwarz than of Typsiles; in both cases we must be content with the mere names.

But here there is nevertheless a slight difference. "Schwarz" belongs to the names which are so common that they hardly bear the stamp of individuality. Schwarz is a name like Brown or White, like Smith or Jones, like Miller or Baker.

Typsiles, on the contrary, has a meaning. The name is not of Jewish, but of Greek origin, when we consider Typto or Psilos, or regard it as a compound of the two, or of two similar words.

The name points to the Levant, to the Byzantine empire—to Constantinople, which at that time not yet conquered from the Turks, had still an active inter course with the West; we find, for instance, Byzantine coins everywhere, from Hungary and Roumania to Denmark and Sweden, and thence to Portugal and Spain. The old German shrines of relics are of Byzantine origin. So also the old imperial crowns. And the Hungarian king's crown, so celebrated for its age and adventures (it was several times sold, stolen, pawned, conquered, robbed, hidden, and yet always reproduced), and regarded by every good

Hungarian as sacred, is of Byzantine origin.

It is a fact that the Byzantines possessed an explosive substance closely related to modern gunpowder, as it came into use in the middle of the fourteenth century in Germany, and middle and Western Europe.

These circumstances lead us to the conjecture that the said Typsiles, be he of Jewish, or Greek Catholic, or Roman Catholic confession—for faith has nothing to do with gunpowder—came from the Orient, and brought thence a knowledge of the preparation of Greek fire into the free imperial city of Augsburg. the metropolis then of the Alemannic countries in Germany, where, by modifications of the technical methods employed, he effected the preparation of our gunpowder.

I do not intend to write an account of the Greek fire, or the science of gunnery in Constantinople, which passed from the Byzantines to the Turks (as did, for instance, the dome of the churches, and much else), but only, *en passant*, to insert two interesting notices.

The "Greek fire" played its part on into the nineteenth century.

During the Greek war for independence in the twenties, the Greeks obtained only occasional successes by land, and these did not prove to be lasting. The separate bands of the armatoli, klephts and palikari, brave as they were, soon dispersed again. The truly decisive triumphs of more permanent effect were gained at sea, where a Miavlis and a Sachturis delivered murderous battle to the fleets of Chosren and Ibrahim; and here it was that the activity of the Greeks triumphed over the lethargy of the Turks, the small vessels of the Greeks, so capable of manœuvering, over the colossal, unwieldy and heavy vessels of the Turks; *and principally by means of fire-ships and the Greek fire.*

These small fire-ships, furnished with this combustible, each manned by nine, or at most twelve men, swarmed about the large Turkish ships, surrounded them on all sides and endeavored to deprive them of wind. The Greeks were familiar with the seas and coasts, those of the mainland as well as those of the innumerable islands, which latter had furnished the trained mariners, men of bravery and skill, inured to the perils of war and the sea, whose wants were so few that a handful of black olives sufficed for a day's subsistence. They were versed in the wind and weather of these seas, and could anticipate their character for several days, so as to prepare combined plans of operations in advance. The Turks, on the contrary, generally rode at anchor. "To anchor suits best the believers in Fatalism," (Mouiller convient aux adeptes du Fatalism) says the French Vice-Admiral Jurien de la Gravière, in his highly interesting contribution to the history of the Orient, from 1815 to 1830, which he has furnished in his book "La Station du Levant."

When the Turkish ships, finding themselves surrounded by the Greek fire ships, overcoming their fatalistic lethargy, finally put themselves in motion, it was generally too late to escape them by a precisely executed manœuvre. The fire-ship knew how to attach itself and its fire—its Greek fire—which burned on and exploded even under water, so skillfully that it could not be gotten rid of. The nine or twelve men in the fire-ship pulled rapidly out of danger in a light boat, while the Greek fire blew the Turkish vessel into the air, or at least tore open a breach of several meters in extent, and thereby usually succeeded in sinking it.

In our torpedoes and torpedo-boats we observe a new form and application of the Greek fire-ships and Greek fire, which has possibly entirely changed naval warfare. At all events the above-mentioned Jurien de la Gravière thought it possible to predict as much. Meanwhile the Germans have every reason to be grateful for the invention of torpedoes, for in 1870 they successfully protected and defended their coasts and seaports.

So much for the notice in regard to *the history of the Greek fire.*

The second notice relates to *the artillery of the Turks.* In the palmiest days of the Turkish Empire, in the fifteenth and sixteenth centuries, the Turkish army excelled in cavalry and artillery. As early as the fifteenth century a gun-foundry existed in Constantinople. In Turkish it is called *top-hané.* In the ear of the Turk the cannon shot does not sound as in our own, "bang," but "top." *Top* is the gun, and *hané* the house. Hence, "gun-house"; and this is precisely what "Katzenstadl" signifies in Augsburg. In the sixteenth century this gun-foundry, this *top-hané,* lying in the suburb Pera, enjoyed an extraordinary celebrity, and the writers of the day (the Genoese Giovanni Antonio Menavino, for instance) do not fail to add to their notice of this gun-foundry, that they were Greek Jews or Jewish Greeks who conducted the entire establishment, namely, the casting of cannon and the preparation of gunpowder, thus furnishing the elements of war and destruction to the hereditary and arch-fiend of Christendom, as the Turks were called, although then and thereafter in alliance, or at least in most cordial harmony, with the "most Christian King" of France. Here certain remarks are pertinent, which I hesitate to communicate. They may be oil on the flames of our anti-semitics of to-day. At all events these remarks cast a peculiar, even somewhat comic, retrospective light on the fact that it was also, as Clemens Jäger informs us, a Greek "Jew named Typsiles," who furnished the Christians of the West their elements of destruction and war to be used against the Mohammedans of the East.

The matter is therefore compensated.

Let us return, after the communication of these Greco-Turkish notices, from the East to the West, to Germany, to Augsburg. That this metropolis of the Alemanni, like Nürmberg, the metropolis of the Franks, stood then, in the fourteenth century, on the pinnacle of arts and manufactures in Germany, is an indisputable fact. Nürmberg was celebrated for the discovery of painting on glass, Augsburg for that of linen or rag paper (in contradistinction to the old parchment or the East Indian cotton paper). Even this claim is contested by other German cities—Ravensburg, for instance, which can produce a register of the year 1324 written on rag paper, and a linen paper mill of the year 1412. But the claims of Augsburg rest on older documents, namely—city accounts of the year 1320, undoubtedly genuine, and written on linen paper. It also possesses such a document of 1330, and many from 1360 on. In short, there is no doubt that Germany can produce the oldest documents on linen paper—older than those produced by Spain and Italy —and that, among the competing German cities it is Augsburg again which contains the oldest of these possessions. The importance of this discovery is apparent when it is remembered that the art of printing would not have spread so rapidly so soon after its discovery, had not linen paper, which surpasses parchment paper in cheapness and cotton paper in durability, already existed.

This same Augsburg, which rejoices in the oldest linen paper, rejoices also in the oldest cannon, *i. e.*, machines from which, *by means of gunpowder*, balls were fired at the enemy. These were then called "Katzen," or "Büchsen" (generally written "Puchsen," "Buchsen," or "Pugxen"). At first they were of wood with iron hoops, and threw stone balls. Augsburg made use of such machines as early as 1372, in the war against the Bavarian dukes. This is attested by the historian Adelzreiter, and confirmed by the city accounts, in which it may also be seen that the gunpowder manufactured by the city was made from saltpetre. In the city accounts of 1377 "grosze Büchsen," *large* guns, which the city ordered to be *cast*, are already mentioned, hence *metallic* cannon. There also existed a "Büchsen meister," or a master-gunner, appointed by the city.

I select the following extracts from a valuable little paper on "Augsburg and its Former Industries," long ago out of print and forgotten, written and published, under commission from the city, by the industrious city recorder, Theodore Herberger, in 1852, on the occasion of the exposition of arts and manufactures of the Bavarian district of Suabia and Neuberg, which is based upon an accurate study of the archives there, namely, the city accounts.

In 1371 the city had expenditures "for saltpetre for the guns," for saltpetre for the manufacture of powder for the guns. In the account 20 guns are mentioned as being used in firing; moreover, "Trinkgelder" (pour boire) for the vassals who served these guns. The expenditures for the wooden frames on which the guns were supported are reckoned in the account. A year later, 1372, 400 shot were cast for the guns; lead "for casting" occurs in the account, saltpetre and "wilder schwefel" (wild sulphur) for gunpowder. One year later, 1373, the expenditure for copper, lead, "and other material" is reckoned in the account "for 4 guns. Another year later there occurs in the accounts an item "for a mortar, in which powder for cannon is pulverized." Many such and similar items may be cited to show how far advanced Augsburg was when the art of firing with heavy guns began. Master Walther, the master-gunner, was not only paid, in 1373, the uncommonly large sum of 160fl., but also received a special present in cloth for constructing the guns ordered, and inspecting the preparation of gunpowder in the court of a "canon of St. Moriz." An unusual number of large cannon was manufactured, according to the accounts, in the years 1410 and 1414, and in the year 1416 the master-gunner, Ott, who was also employed to cast bells in foreign cities, cast several large pieces. All this proves the early date of an immense trade in this department. An especially remarkable man appears in Augsburg in the year 1436. Master Heinrich Roggenburger, the master-gunner. His office is more particularly "the casting of guns, large and small," and the firing of them "as dexterously as has ever been seen;" he can also prepare the powder therefor.

Besides, he is a man remarkably well versed in the technicalities of his art in other respects also, and in his letter of admission he is recommended for the following qualities: He can "make cast and projectile apparatus, large and small, the like of which was never seen in German lands, for this apparatus stands still after the throw, without moving or altering its position, and not requiring to be bound or held;" these machines throw masses of five or six hundred-weight; besides, he makes lifting-machines, by means of which a hundred hundred-weight may be lifted from or upon a wagon; also shields for guns and war chariots, and bridges which may be carried over land and laid over ditches or running water. Moreover, he understands the building of houses and towers, water-mills, windmills and horse-mills, and can make cast, earthen and wooden water conduits to supply the water of wells to hill and valley. Roggenburger received a yearly salary of 110 fl. In the year 1502 the town had a foundry of its own built, which was called Katzenstadl. Here, according to the account of his contemporary, Clemens Sender, Niklas Oberacker cast one hundred metallic pieces and a mortar; among the larger pieces were several forty feet in length. The most noted of all the gun-founders of Augsburg was Gregor Löffler. He was much occupied, not only in Augsburg, but also in foreign countries. In the year 1529 the Government called him to Innsbruck. In this year and in 1537 he had orders to recast all the old pieces which the Emperor and King Ferdinand had in the Tyrol. Among the newly cast cannon were "Karthaunen," capable of firing a shot of an hundred-weight. This work gained for him such approbation that he was entrusted with casting the statues designed to decorate the tomb of the Emperor Maximilian.

Thus far the recorder Herberger. The statues in Augsburg cast by Gregor Loffel are, nevertheless, not identical with those colossal life-statues which now surround the tomb of the "last of the knights" in the Franciscan church at Innsbruck, the authors of which were the brothers Stephen and Melchior Gcdl. The statues of Löffler, representing various saints, twenty-three in number, are found in the same church, in the so-called "Silver Chapel," on the south wall.

I will not further expand this chapter on Augsburg gunpowder and Augsburg ordnance; whoever desires to pursue the subject further, him I refer to the Augsburg chronicles of the fourteenth and fifteenth centuries, published by Professor Karl Mayer.

I hasten to conclude. I am aware that this unassuming chat does not solve the problem, but only brings us a trifle nearer the solution. I only desired to instigate doubt and investigation.

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